Performance Analysis of the IEEE 802.11e Enhanced Distributed Coordination Function using Cycle Time Approach [†]

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Abstract

The recently ratified IEEE 802.11e standard defines the Enhanced Distributed Channel Access (EDCA) function for Quality-of-Service (QoS) provisioning in the Wireless Local Area Networks (WLANs). The EDCA uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and slotted Binary Exponential Backoff (BEB) mechanism. We present a simple mathematical analysis framework for the EDCA function. Our analysis considers the fact that the distributed random access systems exhibit cyclic behavior where each station successfully transmits a packet in a cycle. Our analysis shows that an AC-specific cycle time exists for the EDCA function. Validating the theoretical results via simulations, we show that the proposed analysis accurately captures EDCA saturation performance in terms of average throughput, medium access delay, and packet loss ratio. The cycle time analysis is a simple and insightful substitute for previously proposed more complex EDCA models.

I. Introduction

The IEEE 802.11e standard [1] specifies the Hybrid Coordination Function (HCF) which enables prioritized and parameterized Quality-of-Service (QoS) services at the MAC layer. The HCF combines a distributed contention-based channel access mechanism, referred to as Enhanced Distributed Channel Access (EDCA), and a centralized polling-based channel access mechanism, referred to as HCF Controlled Channel Access (HCCA). We confine our analysis to the EDCA scheme, which uses Carrier

Sense Multiple Access with Collision Avoidance (CSMA/CA) and slotted Binary Exponential Backoff (BEB) mechanism as the basic access method. The EDCA defines multiple Access Categories (AC) with AC-specific Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values, and Transmit Opportunity (TXOP) limits to support MAC-level QoS and prioritization.

We evaluate the EDCA performance for the saturation (asymptotic) case. The saturation analysis provides the limits reached by the system throughput and protocol service time in stable conditions when every station has always backlogged data ready to transmit in its buffer. The analysis of the saturation provides in-depth understanding and insights into the random access schemes and the effects of different contention parameters on the performance. The results of such analysis can be employed in access parameter adaptation or in a call admission control algorithm.

Our analysis is based on the fact that a random access system exhibits cyclic behavior. A cycle time is defined as the duration in which an arbitrary tagged user successfully transmits one packet on average [2]. We will derive the explicit mathematical expression of the AC-specific EDCA cycle time. The derivation considers the AIFS and CW differentiation by employing a simple average collision probability analysis. We will use the EDCA cycle time to predict the first moments of the saturation throughput, the service time, and the packet loss probability. We will show that the results obtained using the cycle time model closely follow the accurate predictions of the previously proposed more complex analytical models and simulation results. Our cycle time analysis can serve as a simple and practical alternative model for EDCA saturation throughput analysis.

II. EDCA OVERVIEW

The IEEE 802.11e EDCA is a QoS extension of IEEE 802.11 Distributed Coordination Function (DCF). The major enhancement to support QoS is that EDCA differentiates packets using different priorities and maps them to specific ACs that are buffered in separate queues at a station. Each AC_i within a station ($0 \leq i \leq i_{max}$, $i_{max} = 3$ in [1]) having its own EDCA parameters contends for the channel independently of the others. Following the convention of [1], the larger the index i is, the higher the priority of the AC is. Levels of services are provided through different assignments of the AC-specific EDCA parameters; AIFS, CW, and TXOP limits.

If there is a packet ready for transmission in the MAC queue of an AC, the EDCA function must sense the channel to be idle for a complete AIFS before it can start the transmission. The AIFS of an AC is determined by using the MAC Information Base (MIB) parameters as $AIFS = SIFS + AIFSN \times T_{slot}$,

where $AIFSN$ is the AC-specific AIFS number, $SIFS$ is the length of the Short Interframe Space, and T_{slot} is the duration of a time slot.

If the channel is idle when the first packet arrives at the AC queue, the packet can be directly transmitted as soon as the channel is sensed to be idle for AIFS. Otherwise, a backoff procedure is completed following the completion of AIFS before the transmission of this packet. A uniformly distributed random integer, namely a backoff value, is selected from the range $[0, W]$. The backoff counter is decremented at the slot boundary if the previous time slot is idle. Should the channel be sensed busy at any time slot during AIFS or backoff, the backoff procedure is suspended at the current backoff value. The backoff resumes as soon as the channel is sensed to be idle for AIFS again. When the backoff counter reaches zero, the packet is transmitted in the following slot.

The value of W depends on the number of retransmissions the current packet experienced. The initial value of W is set to the AC-specific CW_{min}. If the transmitter cannot receive an Acknowledgment (ACK) packet from the receiver in a timeout interval, the transmission is labeled as unsuccessful and the packet is scheduled for retransmission. At each unsuccessful transmission, the value of W is doubled until the maximum AC-specific CW_{max} limit is reached. The value of W is reset to the AC-specific CW_{min} if the transmission is successful, or the retry limit is reached thus the packet is dropped.

The higher priority ACs are assigned smaller AIFSN. Therefore, the higher priority ACs can either transmit or decrement their backoff counters while lower priority ACs are still waiting in AIFS. This results in higher priority ACs facing a lower average probability of collision and relatively faster progress through backoff slots. Moreover, in EDCA, the ACs with higher priority may select backoff values from a comparably smaller CW range. This approach prioritizes the access since a smaller CW value means a smaller backoff delay before the transmission.

Upon gaining the access to the medium, each AC may carry out multiple frame exchange sequences as long as the total access duration does not go over a TXOP limit. Within a TXOP, the transmissions are separated by SIFS. Multiple frame transmissions in a TXOP can reduce the overhead due to contention. A TXOP limit of zero corresponds to only one frame exchange per access.

An internal (virtual) collision within a station is handled by granting the access to the AC with the highest priority. The ACs with lower priority that suffer from a virtual collision run the collision procedure as if an outside collision has occured.

III. RELATED WORK

In this section, we provide a brief summary of the studies in the literature on the theoretical DCF and EDCA function saturation performance analysis.

Three major saturation performance models have been proposed for DCF; *i)* assuming constant collision probability for each station, Bianchi [3] developed a simple Discrete-Time Markov Chain (DTMC) and the saturation throughput is obtained by applying regenerative analysis to a generic slot time, *ii)* Cali *et al.* [4] employed renewal theory to analyze a *p*-persistent variant of DCF with persistence factor *p* derived from the CW, and *iii)* Tay *et al.* [5] instead used an average value mathematical method to model DCF backoff procedure and to calculate the average number of interruptions that the backoff timer experiences. Having the common assumption of slot homogeneity (for an arbitrary station, constant collision or transmission probability at an arbitrary slot), these models define all different renewal cycles all of which lead to accurate saturation performance analysis.

These major methods (especially [3]) are modified by several researchers to include the extra features of the EDCA function in the saturation analysis. Xiao [6] extended [3] to analyze only the CW differentiation. Kong *et al.* [7] took AIFS differentiation into account. On the other hand, these EDCA extensions miss the treatment of varying collision probabilities at different AIFS slots due to varying number of contending stations. Robinson *et al.* [8] proposed an average analysis on the collision probability for different contention zones during AIFS. Hui *et al.* [9] unified several major approaches into one approximate average model taking into account varying collision probability in different backoff subperiods (corresponds to contention zones in [8]). Zhu *et al.* [10] proposed another analytical EDCA Markov model averaging the transition probabilities based on the number and the parameters of high priority flows. Inan *et al.* [11] proposed a 3-dimensional DTMC which provides accurate treatment of AIFS and CW differentiation. Another 3-dimensional DTMC is proposed by Tao *et al.* [12] in which the third dimension models the state of backoff slots between successive transmission periods. The fact that the number of idle slots between successive transmissions can be at most the minimum of AC-specific CW_{max} values is considered. Independently, Zhao *et al.* [13] had previously proposed a similar model for the heterogeneous case where each station has traffic of only one AC. Banchs *et al.* [14] proposed another model which considers varying collision probability among different AIFS slots due to a variable number of stations. Lin *et al.* [15] extended [5] in order to carry out mean value analysis for approximating AIFS and CW differentiation.

Our approach is based on the observation that the transmission behavior in the 802.11 WLAN follows a

pattern of periodic cycles. Previously, Medepalli *et al.* [2] provided explicit expressions for average DCF cycle time and system throughput. Similarly, Kuo *et al.* [16] calculated the EDCA transmission cycle assuming constant collision probability for any traffic class. On the other hand, such an assumption leads to analytical inaccuracies [7]-[15]. The main contribution is that we incorporate accurate AIFS and CW differentiation calculation in the EDCA cycle time analysis. We show that the cyclic behavior is observed on a per AC basis in the EDCA. To maintain the simplicity of the cycle time analysis, we employ averaging on the AC-specific collision probability. The comparison with more complex and detailed theoretical and simulation models reveals that the analytical accuracy is preserved.

IV. EDCA CYCLE TIME ANALYSIS

In this section, we will first derive the AC-specific average collision probability. Next, we will calculate the AC-specific average cycle time. Finally, we will relate the average cycle time and the average collision probability to the average normalized throughput, EDCA service time, and packet loss probability.

A. AC-specific Average Collision Probability

The difference in AIFS of each AC in EDCA creates the so-called *contention zones or periods* as shown in Fig. 1 [8],[9]. In each contention zone, the number of contending stations may vary. We employ an average analysis on the AC-specific collision probability rather than calculating it separately for different AIFS and backoff slots as in [11]-[14]. We calculate the AC-specific collision probability according to the long term occupancy of AIFS and backoff slots.

We define $p_{c_{i,x}}$ as the conditional probability that AC_i experiences either an external or an internal collision given that it has observed the medium idle for $AIFS_x$ and transmits in the current slot (note $AIFS_x \geq AIFS_i$ should hold). For the following, in order to be consistent with the notation of [1], we assume $AIFS_0 \geq AIFS_1 \geq AIFS_2 \geq AIFS_3$. Let $d_i = AIFSN_i - AIFSN_3$. Following the slot homogeneity assumption of [3], assume that each AC_i transmits with constant probability, τ_i. Also, let the total number AC_i flows be N_i. Then, for the heterogeneous scenario in which each station has only one AC

$$p_{c_{i,x}} = 1 - \frac{\prod\limits_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{N_{i'}}}{(1 - \tau_i)}. \tag{1}$$

We only formulate the situation when there is only one AC per station, therefore no internal collisions can occur. Note that this simplification does not cause any loss of generality, because the proposed model

can be extended for the case of higher number of ACs per station as in [7],[11].

We use the Markov chain shown in Fig. 2 to find the long term occupancy of the contention zones. Each state represents the nth backoff slot after the completion of the AIFS$_3$ idle interval following a transmission period. The Markov chain model uses the fact that a backoff slot is reached if and only if no transmission occurs in the previous slot. Moreover, the number of states is limited by the maximum idle time between two successive transmissions which is $W_{min} = \min(CW_{i,max})$ for a saturated scenario. The probability that at least one transmission occurs in a backoff slot in contention zone x is

$$p_x^{tr} = 1 - \prod_{i':d_{i'} \leq d_x} (1 - \tau_{i'})^{N_{i'}}. \tag{2}$$

Note that the contention zones are labeled with x regarding the indices of d. In the case of an equality in AIFS values of different ACs, the contention zone is labeled with the index of AC with higher priority.

Given the state transition probabilities as in Fig. 2, the long term occupancy of the backoff slots b'_n can be obtained from the steady-state solution of the Markov chain. Then, the AC-specific average collision probability p_{c_i} is found by weighing zone specific collision probabilities $p_{c_{i,x}}$ according to the long term occupancy of contention zones (thus backoff slots)

$$p_{c_i} = \frac{\sum_{n=d_i+1}^{W_{min}} p_{c_{i,x}} b'_n}{\sum_{n=d_i+1}^{W_{min}} b'_n} \tag{3}$$

where $x = \max \left(y \mid d_y = \max_z(d_z \mid d_z \leq n) \right)$ which shows x is assigned the highest index value within a set of ACs that have AIFSN smaller than or equal to $n + AIFSN_3$. This ensures that at backoff slot n, AC$_i$ has observed the medium idle for AIFS$_x$. Therefore, the calculation in (3) fits into the definition of $p_{c_{i,x}}$.

B. AC-Specific Average Cycle Time

Intuitively, it can be seen that each user transmitting at the same AC has equal cycle time, while the cycle time may differ among ACs. Our analysis will also mathematically show this is the case. Let $E_i[t_{cyc}]$ be average cycle time for a tagged AC$_i$ user. $E_i[t_{cyc}]$ can be calculated as the sum of average duration for *i)* the successful transmissions, $E_i[t_{suc}]$, *ii)* the collisions, $E_i[t_{col}]$, and *iii)* the idle slots, $E_i[t_{idle}]$ in one cycle.

In order to calculate the average time spent on successful transmissions during an AC$_i$ cycle time, we should find the expected number of total successful transmissions between two successful transmissions

of AC_i. Let Q_i represent this random variable. Also, let γ_i be the probability that the transmitted packet belongs to an arbitrary user from AC_i given that the transmission is successful. Then,

$$\gamma_i = \sum_{n=d_i+1}^{W_{min}} b'_n \frac{p_{s_{i,n}}/N_i}{\sum_{\forall j} p_{s_{j,n}}} \tag{4}$$

where

$$p_{s_{i,n}} = \begin{cases} \dfrac{N_i \tau_i}{(1-\tau_i)} \displaystyle\prod_{i':d_{i'}\leq n-1} (1-\tau i')^{N_{i'}}, & \text{if } n \geq d_i+1 \\ 0, & \text{if } n < d_i+1. \end{cases} \tag{5}$$

Then, the Probability Mass Function (PMF) of Q_i is

$$Pr(Q_i = k) = \gamma_i(1-\gamma_i)^k, \quad k \geq 0. \tag{6}$$

We can calculate expected number of successful transmissions of any AC_j during the cycle time of AC_i, $ST_{j,i}$, as

$$ST_{j,i} = N_j E[Q_i] \frac{\gamma_j}{1-\gamma_i}. \tag{7}$$

Inserting $E[Q_i] = (1-\gamma_i)/\gamma_i$ in (7), our intuition that each user from AC_i can transmit successfully once on average during the cycle time of another AC_i user, i.e., $ST_{i,i} = N_i$, is confirmed. Therefore, the average cycle time of any user belonging to the same AC is equal in a heterogeneous scenario where each station runs only one AC. Including the own successful packet transmission time of tagged AC_i user in $E_i[t_{suc}]$, we find

$$E_i[t_{suc}] = \sum_{\forall j} ST_{j,i} T_{s_j} \tag{8}$$

where T_{s_j} is defined as the time required for a successful packet exchange sequence. T_{s_j} will be derived in (16).

To obtain $E_i[t_{col}]$, we need to calculate average number of users that involve in a collision, N_{c_n}, at the nth slot after last busy time for given N_i and τ_i, $\forall i$. Let the total number of users transmitting at the nth slot after last busy time be denoted as Y_n. We see that Y_n is the sum of random variables, $Binomial(N_i, \tau_i)$, $\forall i: d_i \leq n-1$. Employing simple probability theory, we can calculate $N_{c_n} = E[Y_n|Y_n \geq 2]$. After some simplification,

$$N_{c_n} = \frac{\displaystyle\sum_{i:d_i\leq n-1} (N_i \tau_i - p_{s_{i,n}})}{1 - \displaystyle\prod_{i:d_i\leq n-1} (1-\tau_i)^{N_i} - \displaystyle\sum_{i:d_i\leq n-1} p_{s_{i,n}}} \tag{9}$$

If we let the average number of users involved in a collision at an arbitrary backoff slot be N_c, then

$$N_c = \sum_{\forall n} b'_n N_{c_n}. \tag{10}$$

We can also calculate the expected number of collisions that an AC_j user experiences during the cycle time of an AC_i, $CT_{j,i}$, as

$$CT_{j,i} = \frac{p_{c_j}}{1 - p_{c_j}} ST_{j,i}. \tag{11}$$

Then, defining T_{c_j} as the time wasted in a collision period (will be derived in (17),

$$E_i[t_{col}] = \frac{1}{N_c} \sum_{\forall j} CT_{j,i} T_{c_j}. \tag{12}$$

Given p_{c_i}, we can calculate the expected number of backoff slots $E_i[t_{bo}]$ that AC_i waits before attempting a transmission. Let $W_{i,k}$ be the CW size of AC_i at backoff stage k [11]. Note that, when the retry limit r_i is reached, any packet is discarded. Therefore, another $E_i[t_{bo}]$ passes between two transmissions with probability $p_{c_i}^{r_i}$

$$E_i[t_{bo}] = \frac{1}{1 - p_{c_i}^{r_i}} \sum_{k=1}^{r} p_{c_i}^{k-1} (1 - p_{c_i}) \frac{W_{i,k}}{2}. \tag{13}$$

Noticing that between two successful transmissions, AC_i also experiences $CT_{i,i}$ collisions,

$$E_i[t_{idle}] = E_i[t_{bo}](CT_{i,i}/N_i + 1)t_{slot}. \tag{14}$$

As shown in [9], the transmission probability of a user using AC_i,

$$\tau_i = \frac{1}{E_i[t_{bo}] + 1}. \tag{15}$$

Note that, in [9], it is proven that the mean value analysis for the average transmission probability as in (15) matches the Markov analysis of [3].

The fixed-point equations (1)-(15) can numerically be solved for τ_i and p_{c_i}, $\forall i$. Then, each component of the average cycle time for AC_i, $\forall i$, can be calculated using (4)-(14).

C. Performance Analysis

Let T_{p_i} be the average payload transmission time for AC_i (T_{p_i} includes the transmission time of MAC and PHY headers), δ be the propagation delay, T_{ack} be the time required for acknowledgment packet (ACK)

transmission. Then, for the basic access scheme, we define the time spent in a successful transmission T_{s_i} and a collision T_{c_i} for any AC_i as

$$T_{s_i} = T_{p_i} + \delta + SIFS + T_{ack} + \delta + AIFS_i \tag{16}$$

$$T_{c_i} = T_{p_i^*} + ACK\_Timeout + AIFS_i \tag{17}$$

where $T_{p_i^*}$ is the average transmission time of the longest packet payload involved in a collision [3]. For simplicity, we assume the packet size to be equal for any AC, then $T_{p_i^*} = T_{p_i}$. Being not explicitly specified in the standards, we set $ACK\_Timeout$, using Extended Inter Frame Space (EIFS) as $EIFS_i - AIFS_i$. Note that the extensions of (16) and (17) for the RTS/CTS scheme are straightforward [3].

The average cycle time of an AC represents the renewal cycle for each AC. Then, the normalized throughput of AC_i is defined as the successfully transmitted information per renewal cycle

$$S_i = \frac{N_i T_{p_i}}{E_i[t_{suc}] + E_i[t_{col}] + E_i[t_{idle}]}. \tag{18}$$

The AC-specific cycle time is directly related but not equal to the mean protocol service time. By definition, the cycle time is the duration between successful transmissions. We define the average protocol service time such that it also considers the service time of packets which are dropped due to retry limit. On the average, $1/p_{i,drop}$ service intervals correspond to $1/p_{i,drop} - 1$ cycles. Therefore, the mean service time μ_i can be calculated as

$$\mu_i = (1 - p_{i,drop}) E_i[t_{cyc}]. \tag{19}$$

Simply, the average packet drop probability due to MAC layer collisions is

$$p_{i,drop} = p_{c_i}^{r_i}. \tag{20}$$

V. NUMERICAL AND SIMULATION RESULTS

We validate the accuracy of the numerical results by comparing them to the simulation results obtained from ns-2 [17]. For the simulations, we employ the IEEE 802.11e HCF MAC simulation model for ns-2.28 [18]. This module implements all the EDCA and HCCA functionalities stated in [1].

In simulations, we consider two ACs, one high priority (AC_3) and one low priority (AC_1). Each station runs only one AC. Each AC has always buffered packets that are ready for transmission. For both ACs,

the payload size is 1000 bytes. RTS/CTS handshake is turned on. The simulation results are reported for the wireless channel which is assumed to be not prone to any errors during transmission. The errored channel case is left for future study. All the stations have 802.11g Physical Layer (PHY) using 54 Mbps and 6 Mbps as the data and basic rate respectively ($T_{slot} = 9$ μs, $SIFS = 10$ μs) [19]. The simulation runtime is 100 seconds.

In the first set of experiments, we set $AIFSN_1 = 3$, $AIFSN_3 = 2$, $CW_{1,min} = 31$, $CW_{3,min} = 15$, $m_1 = m_3 = 3$, $r_1 = r_3 = 7$. Fig. 3 shows the normalized throughput of each AC when both N_1 and N_3 are varied from 5 to 30 and equal to each other. As the comparison with a more detailed analytical model [11] and the simulation results reveal, the cycle time analysis can predict saturation throughput accurately. Fig. 4 and Fig. 5 display the mean protocol service time and packet drop probability respectively for the same scenario of Fig. 3. As comparison with [11] and the simulation results show, both performance measures can accurately be predicted by the proposed cycle time model. Although not included in the figures, a similar discussion holds for the comparison with other detailed and/or complex models of [12]-[14].

In the second set of experiments, we fix the EDCA parameters of one AC and vary the parameters of the other AC in order to show the proposed cycle time model accurately captures the normalized throughput for different sets of EDCA parameters. In the simulations, both N_1 and N_3 are set to 10. Fig. 6 shows the normalized throughput of each AC when we set $AIFSN_3 = 2$, $CW_{3,min} = 15$, and vary $AIFSN_1$ and $CW_{1,min}$. Fig. 7 shows the normalized throughput of each AC when we set $AIFSN_1 = 4$, $CW_{1,min} = 127$, and vary $AIFSN_3$ and $CW_{3,min}$. As the comparison with simulation results show, the predictions of the proposed cycle time model are accurate. We do not include the results for packet drop probability and service time for this experiment. No discernable trends toward error are observed.

VI. CONCLUSION

We have presented an accurate cycle time model for predicting the EDCA saturation performance analytically. The model accounts for AIFS and CW differentiation mechanisms of EDCA. We employ a simple average collision probability calculation regarding AIFS and CW differentiation mechanisms of EDCA. Instead of generic slot time analysis of [3], we use the AC-specific cycle time as the renewal cycle. We show that the proposed simple cycle time model performs as accurate as more detailed and complex models previously proposed in the literature. The mean saturation throughput, protocol service time and packet drop probability are calculated using the model. This analysis also highlights some commonalities

between approaches in EDCA saturation performance analysis. The simple cycle time analysis can provide invaluable insights for QoS provisioning in the WLAN.

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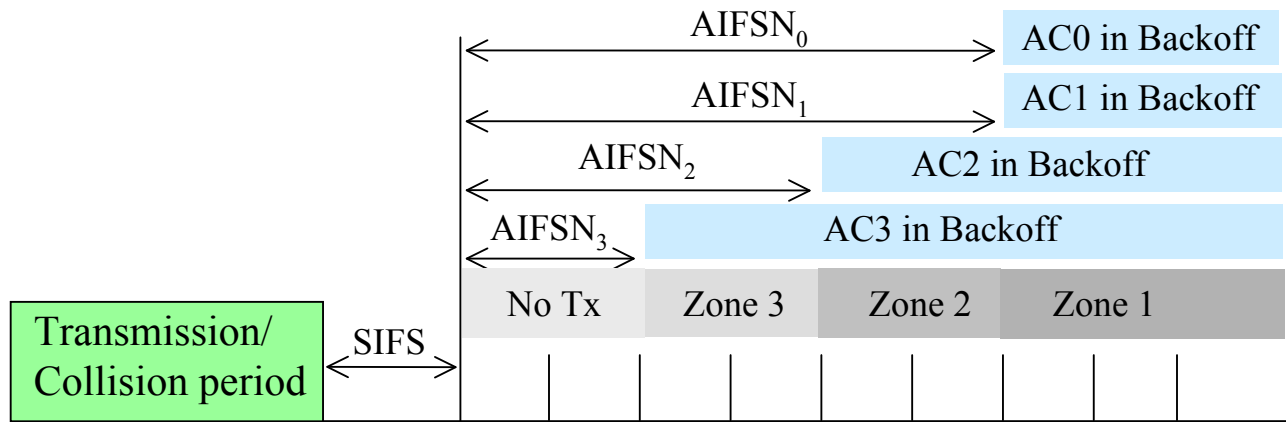
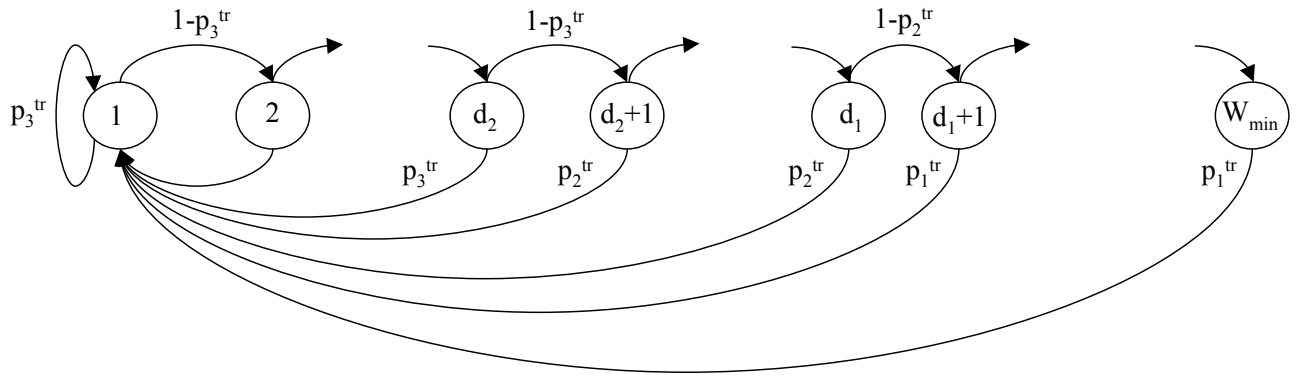Fig. 1.   EDCA backoff after busy medium.

Fig. 2.   Transition through backoff slots in different contention zones for the example given in Fig.1.
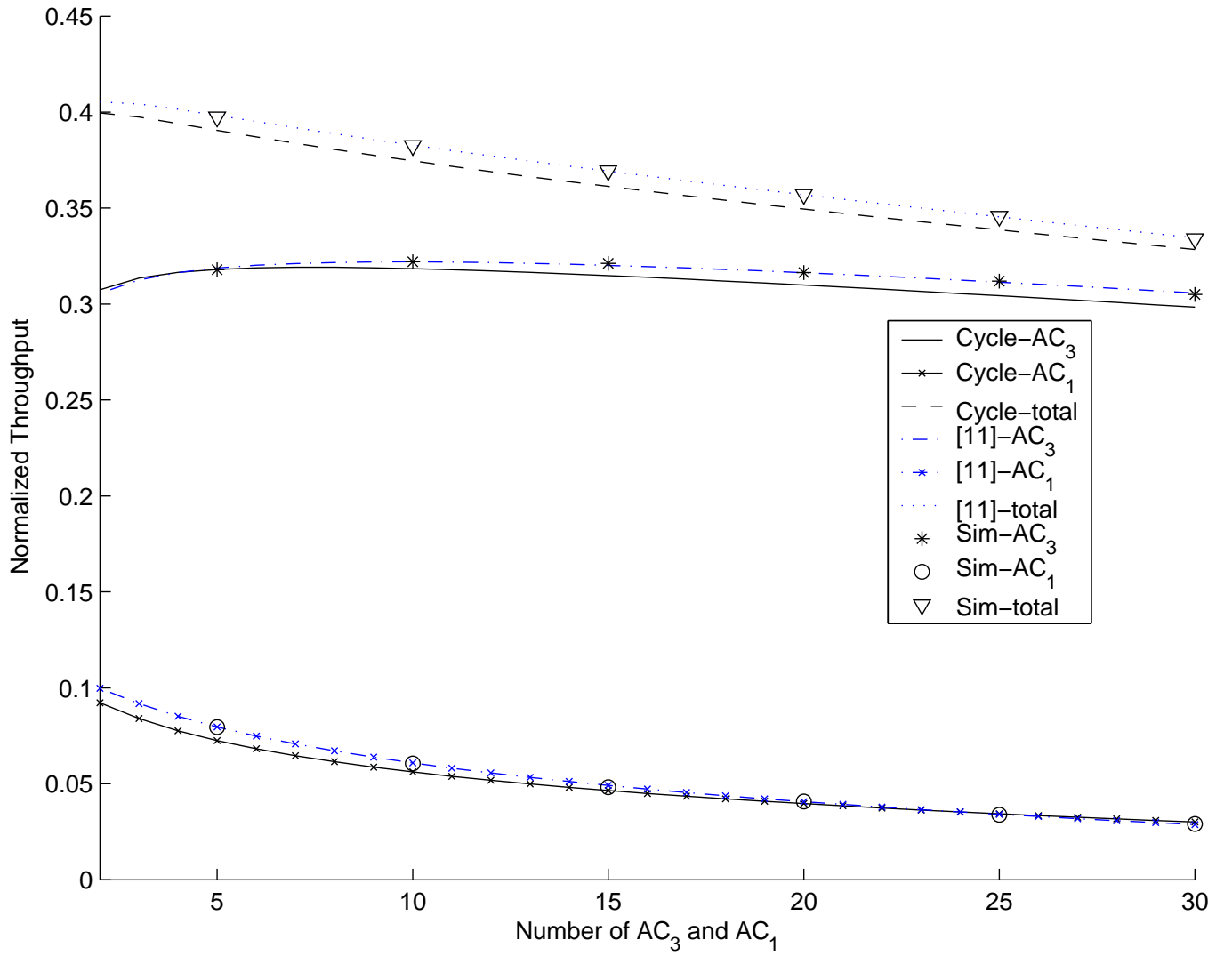
Fig. 3. Analyzed and simulated normalized throughput of each AC when both N_1 and N_3 are varied from 5 to 30 and equal to each other for the cycle time analysis. Analytical results of the model proposed in [11] are also added for comparison.
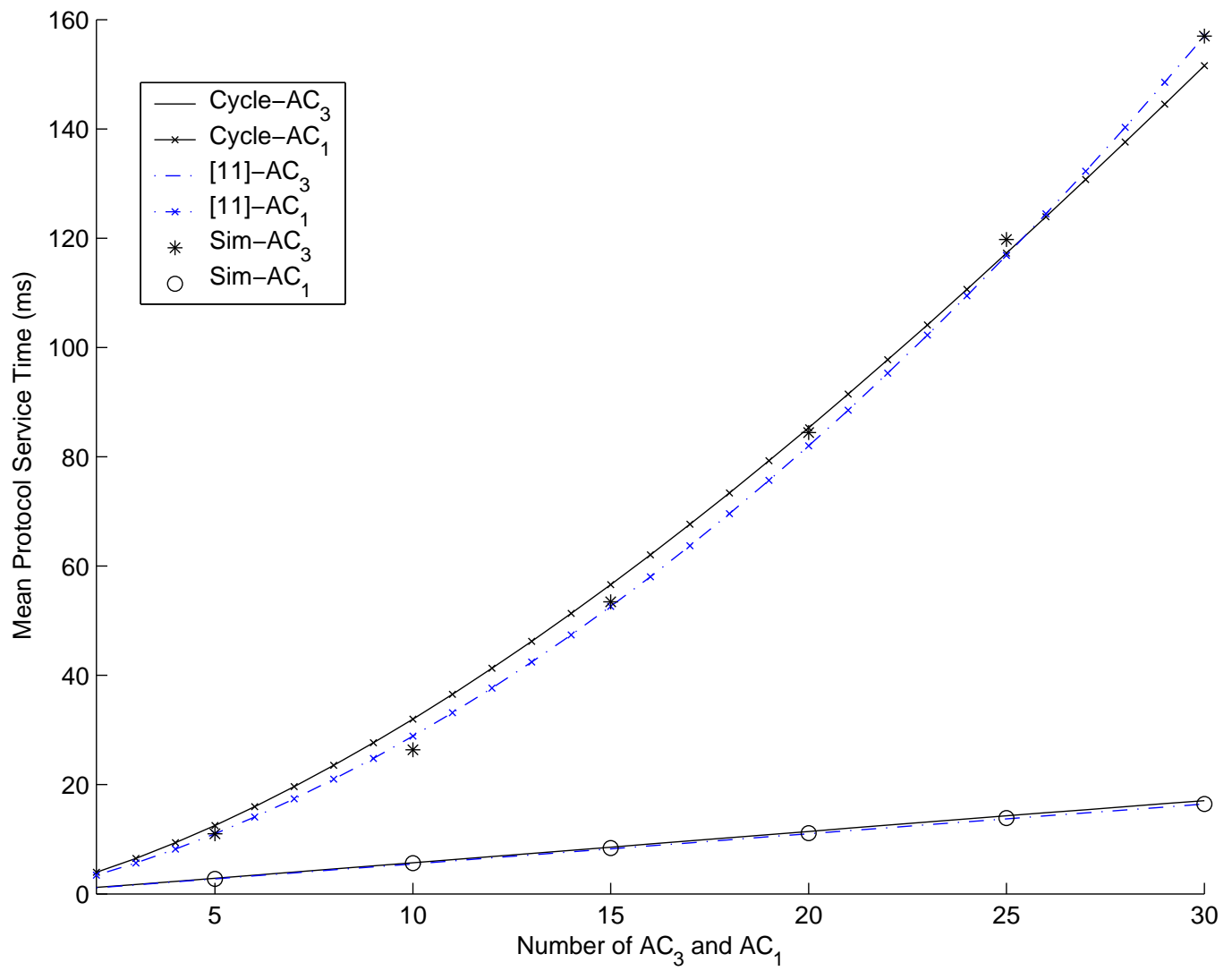
Fig. 4. Analyzed and simulated mean protocol service time of each AC when both N_1 and N_3 are varied from 5 to 30 and equal to each other for the proposed cycle time analysis and the model in [11].
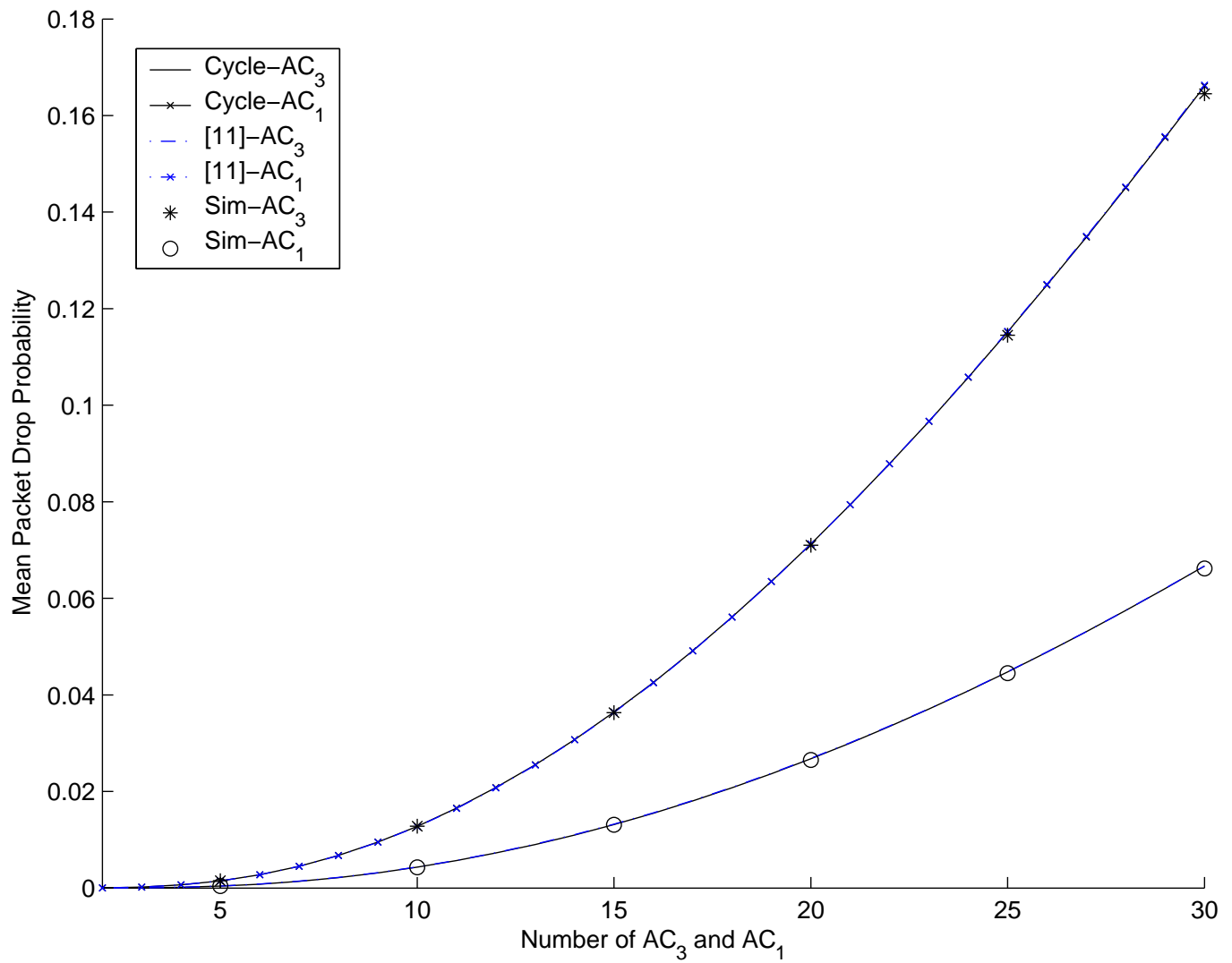
Fig. 5. Analyzed and simulated mean packet drop probability of each AC when both N_1 and N_3 are varied from 5 to 30 and equal to each other for the proposed cycle time analysis and the model in [11].
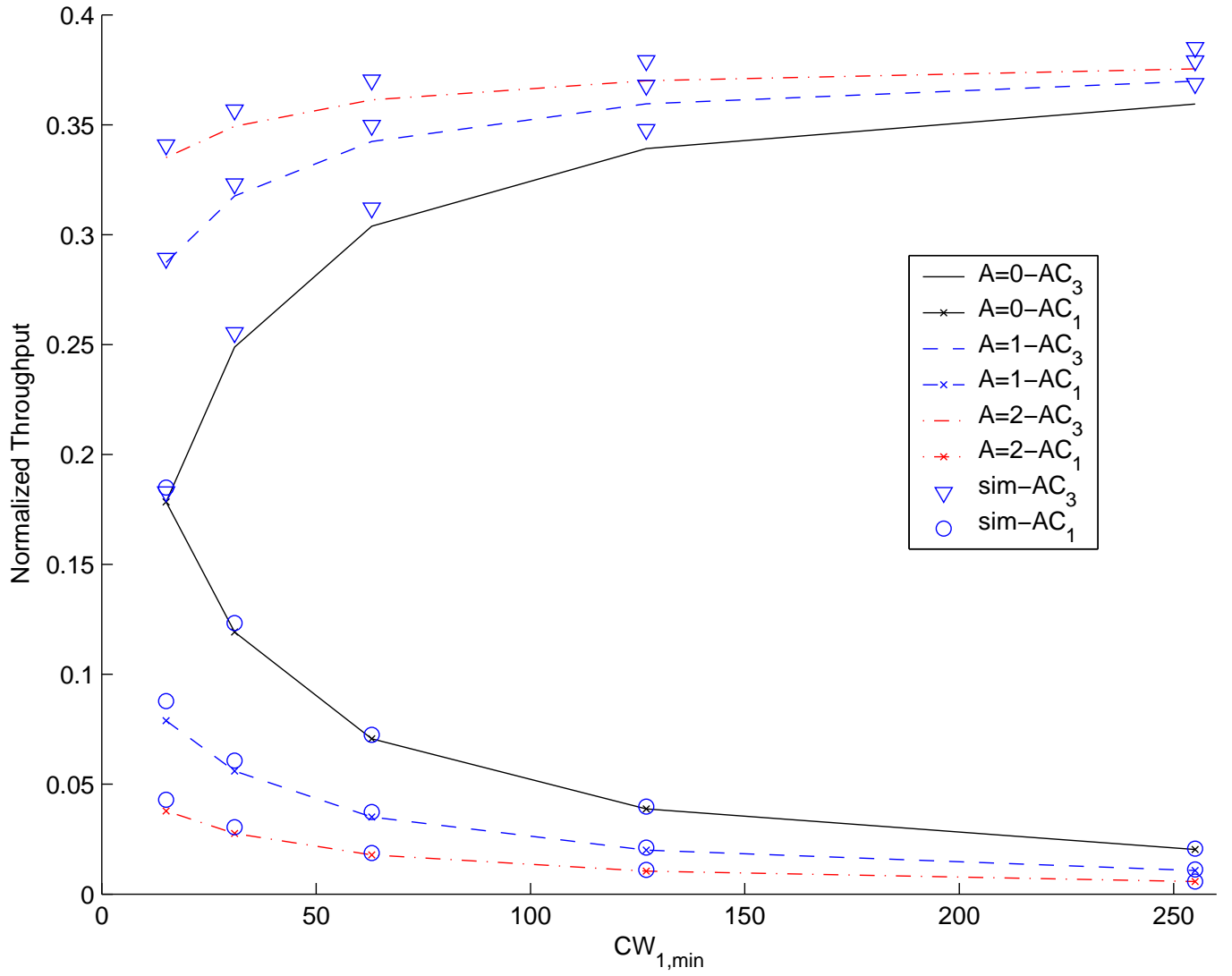
Fig. 6. Analytically calculated and simulated performance of each AC when $AIFSN_3 = 2$, $CW_{3,min} = 15$, $N_1 = N_3 = 10$, $AIFSN_1$ varies from 2 to 4, and $CW_{1,min}$ takes values from the set $\{15, 31, 63, 127, 255\}$. Note that $AIFSN_1 - AIFSN_3$ is denoted by A.
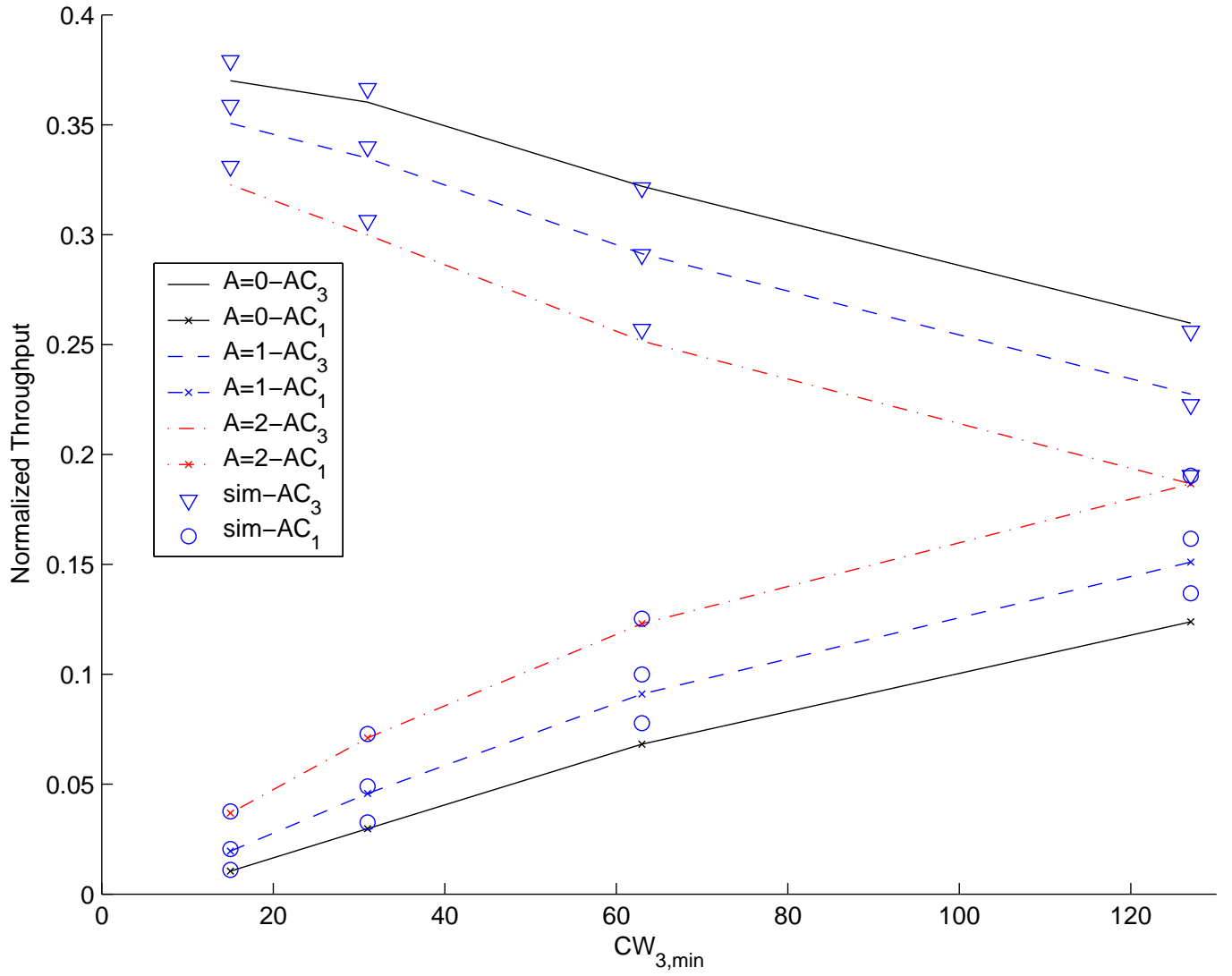
Fig. 7. Analytically calculated and simulated performance of each AC when $AIFSN_1 = 4$, $CW_{1,min} = 127$, $N_1 = N_3 = 10$, $AIFSN_3$ varies from 2 to 4, and $CW_{3,min}$ takes values from the set $\{15, 31, 63, 127\}$. Note that $AIFSN_1 - AIFSN_3$ is denoted by A.